Environmental Research Letters

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OPEN ACCESS

RECEIVED
4 February 2019

REVISED
14 August 2020

ACCEPTED FOR PUBLICATION
9 September 2020

PUBLISHED
23 November 2020

TOPICAL REVIEW

A map of roadmaps for zero and low energy and carbon buildings worldwide

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Keywords: zero energy building, low energy building, zero carbon building, roadmap, evidence map, literature review, ZLECB

Supplementary material for this article is available online

Abstract

Formulation of targets and establishing which factors in different contexts will achieve these targets are critical to successful decarbonization of the building sector. To contribute to this, we have performed an evidence map of roadmaps for zero and low energy and carbon buildings (ZLECB) worldwide, including a list and classification of documents in an on-line geographical map, a description of gaps, and a narrative review of the knowledge gluts. We have retrieved 1219 scientific documents from Scopus, extracted metadata from 274 documents, and identified 117 roadmaps, policies or plans from 27 countries worldwide. We find that there is a coverage bias towards more developed regions. The identified scientific studies are mostly recommendations to policy makers, different types of case studies, and demonstration projects. The geographical inequalities found in the coverage of the scientific literature are even more extreme in the coverage of the roadmaps. These underexplored world regions represent an area for further investigation and increased research/policy attention. Our review of the more substantial amount of literature and roadmaps for developed regions shows differences in target metrics and enforcement mechanisms but that all regions dedicate some efforts at national and local levels. Roadmaps generally focus more on new and public buildings than existing buildings, despite the fact that the latter are naturally larger in number and total floor area, and perform less energy efficiently. A combination of efficiency, technical upgrades, and renewable generation is generally proposed in the roadmaps, with behavioral measures only reflected in the use of information and communication technologies, and minimal focus being placed on lifecycle perspectives. We conclude that insufficient progress is being made in the implementation of ZLECB. More work is needed to couple the existing climate goals, with realistic, enforceable policies to make the carbon savings a reality for different contexts and stakeholders worldwide.

1. Introduction

Achieving ambitious global climate targets by 2050 implies a transition to net zero carbon emissions worldwide. Buildings account for 36% of global final energy consumption and almost 40% of total direct and indirect carbon dioxide (CO_2) emissions (IEA 2019a). In a business-as-usual scenario without further climate policies, global final energy demand from buildings could increase from 116 EJ yr^{-1} in 2010 by 80% in 2050 and up to by 325% in 2100, with electrical uses including cooling taking a more prominent share of demand (Ürge-Vorsatz *et al* 2015, Levesque *et al* 2018).

For the buildings sector, key contributions to decarbonization identified in global assessments[1] include new buildings and areas constructed with

[1]Here we summarize only results from global assessments or with a regional disaggregation different from that in section 4.2 of this paper, whereas region-specific knowledge will be discussed in section 5.

zero energy and positive energy standards, high energy-renovations rates, increased electrification, and deployment of decentralized renewable energy sources (RES) (Wang *et al* 2018). Levesque *et al* (2019) have shown low consumption practices reduce global energy demand from buildings up to 47% by 2050 and 61% by 2100 compared to a scenario following current trends. This strong reduction is primarily accounted for by changes in hot water usage, insulation of buildings, and consumer choices in air conditioners and heat pumps. Other global low energy demand scenarios for buildings are also presented in Grubler *et al* (2018) and Teske *et al* (2015). In fact, the scenarios driven by demand reductions and behavioral changes have clear economic, social, and environmental benefits over technology-driven scenarios (Creutzig *et al* 2016, 2018, Allen *et al* 2017, Mundaca *et al* 2019). In such assessments, the assumption that all new and existing buildings will require no or little energy is typically exogenous, whereas the actual implementation of such building standards is not straightforward: design, construction and operation challenges are still not solved (Butera 2013, Saheb *et al* 2018). The transformation of the building sector has to rely on strategies that find a balance between building standards including: design, construction, and operation, as well as the decarbonization of the energy supply sector (Belussi 2019, Filippidou and Jiménez Navarro 2019). RES are fundamental to this transition: solar, geothermal, bioenergy, and wind should be exploited to produce the energy to meet the building's needs, but they should also be accompanied with a careful building envelope design (Magrini 2020).

The multiple definitions of zero-energy building (ZEB) concepts have been investigated in the recent literature. For example, Pless and Torcellini (2010) explore several different ZEB definitions in the United States (US) context, and Harkouss *et al* (2018) assess the progress of their implementation in Europe and beyond. Wells *et al* (2018) have performed a similar work for Australia. Marszal *et al* (2011) provide a broader overview of definitions, and D'Agostino and Mazzarella (2018) have updated this review, underlining inconsistencies and critical issues among the definitions in the European Union (EU) and the US. Here, we present the most common definitions:

- The Low Energy Building (LEB) concept is based on improving the building envelope to reduce heating and cooling demand, and using high efficiency equipment as well as RES (Chlela *et al* 2009). For new-built this definition translates to a building constructed according to specific design criteria aimed at minimizing the building's operating energy (Sartori and Hestnes 2007).
- ZEB is an energy efficient building able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand. Therefore, when we refer to ZEB, it is implicit that there is a focus on buildings that are connected to an energy infrastructure and not on autonomous buildings (Sartori *et al* 2012). This term leads to the definition of different ZEB buildings depending on the net energy exchange with the energy networks (Sartori *et al* 2012).[2]
- NZEB (Net Zero Energy Building) is a yearly energy neutral building that delivers as much energy to the grid as it draws back (Panagiotidou and Fuller 2013). The word 'Net' underlines the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year (Sartori *et al* 2012).
- nZEBs (nearly Zero Energy Buildings) are those buildings with a very high energy performance and very low amount of energy required. This energy is covered to a very significant extent by energy produced from on-site or nearby renewable sources (EU 2012)
- PEBs (Positive Energy Buildings) are those buildings producing electricity, covering their heating and cooling needs and contributing to the grid stability (EC 2019a) or putting it differently, those with a negative net energy consumption over a typical year.
- Last, the term Zero Carbon Buildings (ZCB) has not been defined clearly in scientific or grey literature yet. In the UK, where the term was first used, net zero carbon emissions over one year are assumed, whereas in Australia, a ZCB is one that has no net annual emissions from the operation of building-incorporated services (Pan 2014).

In the scientific works presented above, the concept of embodied energy is presented as part of the building life cycle. More precisely, Sartori *et al* (2012) suggest an annualized accounting of the embodied energy of the buildings shell, technical building systems, and on-site energy production systems. Other standards and policies for very high energy efficiency are summarized in Grove-Smith *et al* (2018). Based on these definitions, we perform an analysis on how these terms are used in scientific and other studies.

The scientific literature on PEBs is not extensive. The exemplary search ['positive energy buildings' AND (target OR goal)] in ScienceDirect gives only 126 results, of which 18 are review articles.[3] However, the results increase substantially if the search includes ('Net Zero Energy Building' OR NZEB). Beyond the above presented papers addressing definitions,

[2]In this respect the term Net ZEB can be used to refer to buildings that are connected to the energy infrastructure, while the term ZEB is more general and may as well include autonomous buildings.

[3]Search performed on 2020–07-06. It is however growing: when the paper was first designed in January 2019 the query gave 101 results, of which 12 were review articles.

we have identified some reviews, which differ in geographical scope, boundary conditions and scenarios, targeted goals, and which many times focusing on study cases.

There are reviews that tackle the integration of RES in buildings (Cao *et al* 2016). Others assess key measures and potentials for renovating towards NZEB or constructing new NZEB, with focus on different solutions—e.g. optimizing home technologies (Lu *et al* 2015, Alfaris *et al* 2017) or technologies for fresh air supply (Liu *et al* 2018). Other studies also include costs (D'Agostino and Parker 2018) or stages of the lifecycle—e.g. early phase and usage phase (Oh *et al* 2017) and embodied energy (Chastas *et al* 2016). Some literature on implementation at multi-building scale—block, urban, regional—is also available; Kylili and Fokaides (2015) present the potential contribution of the ZEB principle towards achieving smart cities in Europe and Koch *et al* (2012) for a neighborhood. Other studies explore the optimal balance between the reduction of energy needs and the self-sufficiency from RES sources (Belussi 2019, Magrini 2020)

Successful decarbonization of the building sector and implementation of low-energy and carbon standards worldwide will require monitoring the formulation of targets and establishing which factors in different contexts will lead to the achievement of targets. While the above-mentioned existing studies have generated some insight into these complexities, such as technological options available, definitions, and implementations, to date they have been limited in scope. There is no existing summary of targets and roadmaps worldwide, and, thus, no overview of committed actions and knowledge on how to implement the targets set effectively and at scale. None of the existing reviews are systematic (*i.e.* use systematic review methodology) and none are global in coverage. Without a comprehensive understanding of current efforts, including which measures work and which do not, there is a risk of wasting funding and resources with limited research-policy links, research utilization, and societal benefit.

In this paper, we will refer broadly to 'zero and low energy and carbon buildings' (ZLECB) to include all the concepts above, thus denoting buildings with *low energy and carbon during their lifecycle*, which requires: i) effective building design, ii) efficient technical systems, iii) on-site production from RES, and iv) low impact material choices. We therefore exclude from the scope of this paper the discussion on the definitions and instead focus on the national and sub-national efforts and targets committed worldwide. Efforts could be technological, including research and development of new technologies, or regulatory. The latter should provide both goals and implementation plans, as well as tools to monitor these, such as building codes or energy performance assessment guidelines. In addition, in this regulatory context, roadmaps are a key instrument when it comes to laying down guidelines and milestones to be achieved.

Roadmaps are usually defined as a plan or strategy used in order to achieve a goal. Generally, roadmaps can have a single or multiple objectives, and they outline and detail the steps to achieve these objectives. In this paper, we define roadmaps as strategic time-based action plans to implement and achieve stated objectives as targets.

The novelty of this work starts with our review methodology, as we make an effort to map and classify the literature worldwide. An additional contribution is the mapping of national and sub-national actions, including cities/municipalities/local authorities/states that, in many cases, have more ambitious goals than nation states. As a result, we include grey literature worldwide, as well as public, institutional and governmental reports.

2. Aim

We address the following primary research question:

> *What is the extent and distribution of existing literature on roadmaps and targets for positive or ZLECBs?*

Using the resulting evidence base, we aim to answer the following secondary research questions:

1. Which roadmaps and targets for positive or ZLECBs exist around the world?
2. At what regional and institutional scales are the current efforts allocated?
3. What is the specific focus of the existing targets and roadmaps?
4. What subsectors or building typologies (e.g. public buildings, offices, apartment blocks, single-family houses, new buildings, existing buildings) are approached in the literature?
5. What are the major gaps in the evidence base from (a) primary research studies and (b) systematic reviews?

3. Methods

We draw on elements of systematic map methodology guidelines from the Collaboration for Environmental Evidence (CEE) (CEE 2018), however, with substantial deviations summarized in table 1. Hence, this effort to map the evidence is not fully systematic, but aims to be an initial exploration of the topic. First, we have conducted the search for scientific literature in only one database, Scopus. A recent comparative analysis of Web of Science and Scopus on the Energy Efficiency and Climate Impact of Buildings shows, however, that only 12% of documents are found in both databases (Cabeza *et al* 2020), suggesting that the documents that our search string would

Table 1. Steps in a CEE evidence synthesis methodology and deviations in this paper.

Step	CEE	THIS STUDY
1	Question formulation	Yes
2	Review scoping	Yes
3	Protocol submission	No, but ROSES protocol is available
4	Search process	Yes (only in Scopus)
5	Article screening	Yes (only by one reviewer)
6	Data extraction	Yes (only by one reviewer) Twice: Abstract and full text levels
7	Critical appraisal	No
8	Synthesis	Yes

retrieve from Web of Science could be quite different. Moreover, Konno *et al* (2020) assess impacts of search strategies relying only on widely used bibliographic platform(s) on effect sizes provided in published environmental meta-analyses, and find that restricting searches to a few, widely used, bibliographic platform(s) may lead to provision of biased estimates of effect sizes. We have tried to mitigate this risk by including studies from grey literature, unpublished data, and non-English-language publications. Second, the screening of articles and data extraction are conducted by a single reviewer—there is a likelihood that bias will be introduced into the process. Conversely, as there is just a single reviewer, incidence of bias in interpretation is likely to be consistent. We aim to mitigate this bias by ensuring that all authors are involved in the design of the synthesis protocol and in assessing and interpreting results. Last, a deviation arises from the fact that metadata typically should not be extracted at the title and abstract level because often abstracts are not reflective of what the paper is actually about. We believe there is a real value in classifying the literature, and we believe it is unlikely that we have misclassified substantial amounts of documents, as we have reviewed many at full text level, both during the scoping study and after. There has been an iterative process to decide the 14 types of documents needed, the boundaries and the definitions.

We conform to the Reporting standards for Systematic Evidence Syntheses (ROSES) (Haddaway *et al* 2018). The different methodological steps summarized in table 1 will be presented below in corresponding subsections.

As illustrated in figure 1, we have performed a scoping study to test the method over steps 1 to 6, then made all necessary adjustments, including suggestions from a reference group (the reference group will be described in section 3.1.3): modified search-string, fine-tuning of study parameters and updated metadata extraction and screening strategy for the final review study. In the scoping study, the screening at Title and Abstract level was conducted in APSIS Scoping Review Helper (MCC 2019), while the review-planning and Screening of Full-Texts was executed using Colandr (Cheng *et al* 2018).

The details of the final review process are described below.

3.1. Search

3.1.1. Scientific literature.

We have followed the PICO guideline for identifying keywords for searches. According to James *et al* (2016), in environmental sciences, the most common question to answer is 'what type of impact an intervention or exposure has on the environment', and generally four key elements must be specified: what is the affected population (P), what is the intervention/exposure (I/E), what is the comparator (C), and what is the outcome (O)?.

We have therefore developed sets of keywords related to: (1) positive and net energy building, and (2) roadmaps and targets. For each set of keywords, we have developed a search string combining—through the Boolean operator OR—synonyms for each set (and possibly categories or examples of them), and then we piloted such a search string structured according to the PICO elements, and tested it in Scopus.

Elements of our primary question are: Population: Buildings; Intervention: Roadmaps and targets; Outcome: Various ZLECB. Although a 'Comparator' criterion is also usually part of the inclusion criteria, it was excluded from this study since the nature of the question and the type of documents were found to be heterogeneous.

3.1.1.1. Buildings sector.

'building*' OR 'house*' OR 'residential' OR 'domestic' OR 'service*' OR 'tertiary' OR 'public'.

3.1.1.2. Roadmaps and targets.

('decarb*' OR 'carbon*' OR 'climat*' OR 'energy') W/3 ('potential' OR 'mitigat*' OR 'policy' OR 'sav*' OR 'pathway*' OR 'scenario*' OR 'roadmap*' OR 'regul*' OR 'strateg*' OR 'normat*' OR 'legisl*' OR 'target*' OR 'goal*' OR 'action plan*').

3.1.1.3. Low energy or low carbon buildings.

('positive energy' OR 'zero' OR 'net zero' OR 'ZEB' OR 'NZEB' OR 'neutral*') W/3 ('building*' OR 'block' OR 'standard' OR 'energy').

We have combined the sets above with the Boolean operator AND, and identified keywords that lead to unappropriated documents as well. We have combined the following with the Boolean operator AND NOT:

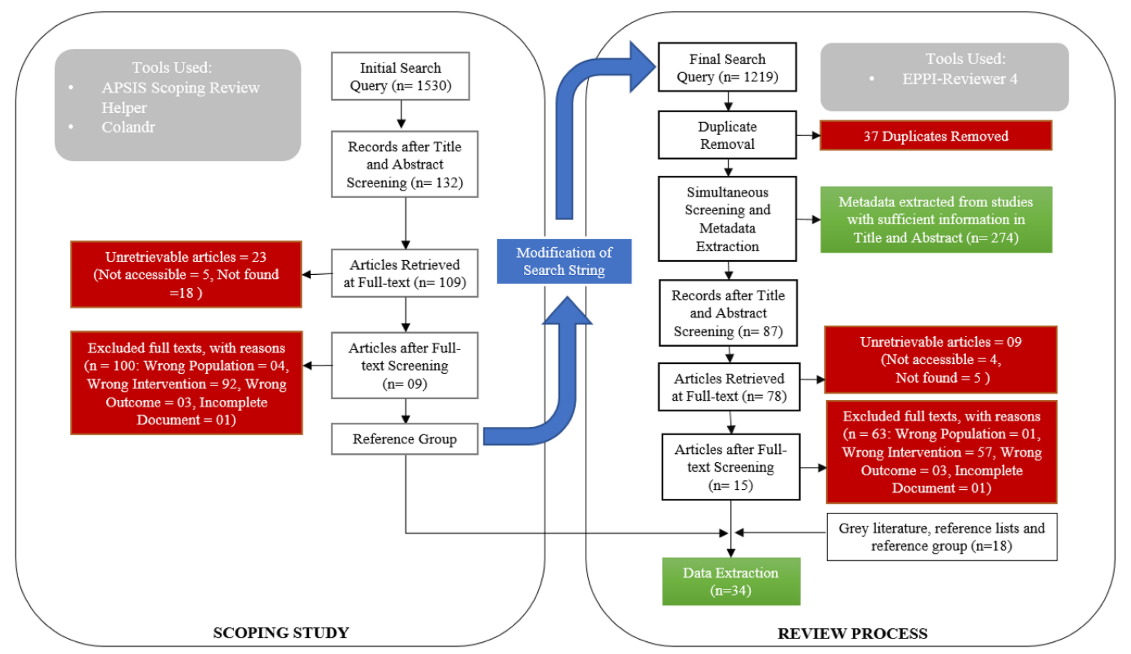

Figure 1. Workflow process diagram.

('building on' OR 'building upon') OR 'radioactiv*' OR 'agricultur*' OR 'underground water' OR 'livestock*' OR cropland OR forest OR aerodynamic OR biodiversity OR 'road design' OR 'power sector' OR 'mineral*' OR 'CO2 capture' OR 'carbon capture' OR 'CCS' OR earthquake OR 'health risk*' OR engine OR 'truck*' OR biogas OR bio-based OR 'crop*' OR 'fish*' OR marine OR 'drink*' OR 'business performance' OR 'company performance' OR 'organizational conduct' OR 'managerial innovation' OR aquaculture OR 'manufact*' OR 'in-house' OR rail OR logistic OR 'fleet' OR 'gasoline' OR 'transportation' OR 'nursing' OR 'foreign trade' OR 'export intensity' OR 'firm performance' OR 'morbidity' OR 'malnutrition' OR 'remote sense*' OR '3D model*' OR 'financial sector' OR 'financial development' OR 'fiscal reform' OR banking OR 'housing price' OR 'house pric*' OR 'house market' OR 'housing market' OR 'housing tenure' OR 'tenure choice' OR 'terrorist*' OR 'hostage*' OR 'consumer satisfaction' OR 'productivity' OR 'cognitive habilit*' OR 'foreign aid' OR 'health status' OR 'agriculture*' OR 'bilateral trade' OR 'trade balance' OR 'corporate reputation*' OR 'bicycle network' OR 'transport mode' OR 'commut*' OR 'farmer*' OR 'medical rehabilitation' OR 'medicare' OR 'health insurance' OR 'health policy' OR 'disease*' OR obesity OR disability OR cybersecurity OR 'political economy' OR 'internet filter*' OR 'political development' OR 'tourism demand' OR 'overnight stay*'.

3.1.1.4. Fields.
We have excluded the following fields: Medicine, Biochemistry, Immunology, Nursery, Veterinary. We did not explicitly include specific fields, but our search in Scopus returned the highest number of responses in the following fields: Engineering ($n = 770$), Energy ($n = 553$), Environmental Science ($n = 296$), Computer Science ($n = 111$), Social Sciences ($n = 106$), Material Science ($n = 90$), Mathematics ($n = 87$), and Earth and Planetary Sciences ($n = 75$).

3.1.1.5. Publication year.
We have only reviewed results published after 2010 (inclusive), as to gather recent knowledge and roadmaps and targets still in force.

The search has been conducted in Scopus database and provided a total of 1219 documents.

3.1.2. Grey literature.
We have identified grey literature via non-scientific search engines (Google, Google Scholar, baidu.com and duckduckgo.com), by hand searching the websites of specific organizations, by looking for relevant literature in the bibliographies of included documents, and by directly communicating with experts in the below-described reference group.

The searches have been conducted in English, and Chinese, but returned some documents in Marathi which were disregarded. The process was however not systematic and was repeated many times during the duration of the work, so that keywords, number of results, and other details have not been recorded.

3.1.3. Reference group.
The reference group consisted of experts from China, France, India, Sweden, USA, and Brazil (see

Table 2. Summary of key themes and terms in the excluded documents, including number of documents (n).

Reason for exclusion	n	Key terms
Excl: Population	*330*	
Building Integrated Photovoltaics	44	BIPV, solar PV, PV systems
Heating, Ventilation, and Air-Conditioning	62	air conditioning systems, cooling systems, heating systems, heat pumps, thermal systems, ventilation, heat exchanger, HVAC
Energy Management	46	battery storage, energy management, microgrids, load management systems, smart grids, smart controllers
Building Envelope	72	architectural components, building envelope, facade, glazing, insulation, phase change materials (PCM), roofs, windows
Excl: Intervention	*741*	
ZLECB Design Studies	101	architectural design, design, design optimization, design recommendation, design strategy, MCDA design, design proposals
LZECB Simulation or Modeling Studies	188	simulation, algorithm, model predictive control (MPC), optimization, performance analysis, performance assessment, modeling

Acknowledgements) who were presented in two occasions over an online presentation with the results of the scoping study and the final study respectively. The reference group was asked to provide the following:

- Relevant keywords to be used as search terms. These were incorporated into the modified search strategy, as shown in figure 1.
- Suggestions and confirmation of relevant grey literature, including institutional websites, direct literature tips, and key contact persons.
- Suggestions and confirmation of roadmaps and targets around the world.
- Suggestions on visualization of results.
- Comments on the main conclusions.

In both occasions, the input from the reference group was collected during the meeting and in follow-up emails and incorporated in the analysis.

3.2. Article screening

We captured all resulting documents ($n = 1219$) into EPPI-reviewer,[4] removing duplicates (37 duplicates). The documents have been screened for relevance at title and abstract level, following the inclusion criteria:

- Relevant population
- Relevant intervention
- Relevant outcome

Documents focusing on the theoretical design or design methodology of new buildings were excluded from the metadata extraction. Documents which were purely simulations and did not have an implementation aspect were also excluded. Documents which focused only on technologies or technological measures were also excluded from the metadata extraction and other sections of this study. Excluded documents are summarized in table 2.

After the title and abstract screening, we identified 87 documents as relevant and retrieved their full text. Nine documents could not be retrieved (figure 1). We screened the full text of the remaining 78 documents, and we selected 15 documents for data extraction.

3.3. Coding strategy

Data was extracted at two levels (see table 1), below described in corresponding subsections.

3.3.1. Data extraction.

We have extracted, looking at the title and abstract text level, four key categories of data for 274 documents:

- Type of study (14 types): (1) Real Roadmap Document; (2) Regulation, Label, or Standard document; (3) Policy Document; (4) Policy Analysis Document, which analyses or scrutinizes a Policy Document; (5) Policy Implications Document that assesses the effects of a policy; (6) Policy: Other—document talks about other aspects of policies not mentioned above; (7) Recommendation Document provides a recommendation to inform policy or planning; (8) Demonstration Project Document talks about the real implementation of ZLECB projects; (9) Case Study: Retrofit Document is a real-life case-study of an already existing building being converted to ZLECB; (10) Case Study: Performance Assessment Document assesses the performance of an implemented ZLECB; (11) Case Study: District or Campus Document is a Case Study, but refers to a city-district, educational or institutional campus; (12) Case study: Other—document is a case-study that could not be classified as any of the case-studies above; (13) Other: Miscellaneous—document is a

[4]EPPI-Reviewer 4: systematic review software. [online] https://eppi.ioe.acuk/eppireviewer-web/home

survey, business model, progress report or assessment, or other study which informs decision-making; (14) Definition Document—states, analyses or recommends definitions for different typologies, or geographical areas for ZLECB.

- World regions, following 5 regions and 22 subregions:[5] (1) Africa and Middle East (Eastern Africa, Middle Africa, Northern Africa, Southern Africa, Western Africa); (2)Asia and developing Pacific (Central Asia, Eastern Asia, South-Eastern Asia, Southern Asia, Western Asia); (3) Eastern Europe (Eastern Europe and West-Central Asia); (4) Latin America and the Caribbean (Caribbean, Central America, South America); and (5) more developed regions (North America: USA & Canada, Greenland & Bermuda + Others; Europe: Northern and Western Europe, Southern Europe and Eastern EEU; Asia-Pacific developed: Australia & New Zealand, Others).

As there was a single reviewer, any ambiguous or confusing citations were consulted with another author. Although the classification was eventually made at abstract and title level, we have looked at many of them at full text level, both during the scoping study and the final review. There has been an iterative process, combining full text and abstract analysis, to decide the 14 types of documents needed, the boundaries and the definitions.

The resulting literature map is presented in section 4.1.

3.3.2. Target assessment.
From the full texts of the 34 included documents (scope and final search, grey literature and reference lists, see figure 1), we have identified a total of 117 roadmaps, policies or strategies from 37 countries. For these, we have extracted, also by screening at full text level, the following additional data:

- Country and location,
- Name of roadmap, policy or plan
- Organization and organizational level
- Year of issue
- Goals and targets. We follow the classification of targets given by IEA EBC Annex 56 methodology (de Almeida *et al* 2017) which provided guidelines to policy makers and for policy objectives for reducing greenhouse gas (GHG) emissions from buildings and included the following types of policy objectives:

  (1) Increase the energy efficiency of both new and existing buildings;
  (2) Increase the energy efficiency of appliances;
  (3) Encourage energy distribution companies to support reduction of emissions from the building sector;
  (4) Target attitudes and behavior change; and
  (5) Substitute fossil fuels with RES.

The resulting narrative review is presented in section 4.2.

3.4. Mapping and presentation

We have provided statistical and narrative descriptions of various characteristics, namely: geographical scope, variable studied, methodological approach and key determinants. We have visually presented our mapping by using an evidence mapping software Wizzard (http://eppimapper.digitalsolutionfoundry.co.za/#/). Through such visualization we have identified evidence gaps (underrepresented sub-topics that warrant primary studies) and clusters (well-represented sub-topics that indicate potential for synthesis via full systematic reviews).

The resulting visual map of the literature is presented as Supplementary Material (available online at stacks.iop.org/ERL/15/113003/mmedia).

4. Results

4.1. Literature map

Figure 2 presents the frequency of the type of documents, per world region. Most of the total of 274 documents studied were marked for multiple types of documents, therefore the total displayed is higher than 274 ($n = 427$). The documents are also referenced in the visual map given as Supplementary Material.

The type of documents with highest frequency is recommendations ($n = 71$) made by researchers and academics to inform policy makers. Other significant study types are performance assessment case studies ($n = 65$) done to either establish design practices or prove the efficiency of demonstration projects; the latter is the next highest frequency study type reported. Together, the different types of case studies and demonstrations projects are the most frequent type of document, see Ürge-Vorsatz *et al* (2020) for a recent review of case studies. No official policy documents were retrieved and only 9 roadmaps or action plans were found, probably because we have used a scientific database.

An analysis of the geographical focus shows that only 4% of the documents have global coverage ($n = 16$). The vast majority of the documents focus on Region 5, more developed regions (76% or $n = 325$), including Europe subregions (Southern Europe and Eastern EU, $n = 125$; Northern and Western, $n = 109$), USA & Canada ($n = 73$), and Australia & New Zealand ($n = 18$). Significantly, less documents focus on Region 2, Asia and developing Pacific

[5] Very similar to UN Classification, *i.e.* usually the M49 Standard or ISO 3166.

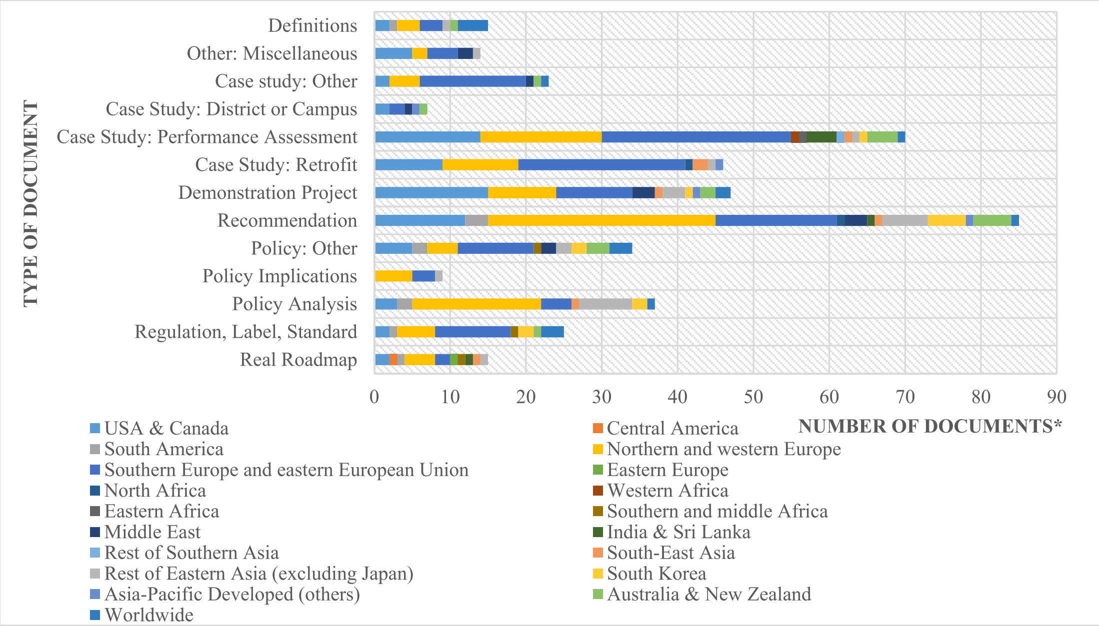

Figure 2. Categorization of documents obtained from Scopus database, by type of document. (*) The total number of documents is higher than 274, because each single document has been coded for all different features and locations included in that document. Based on: Korpal (2020). The documents are also referenced in the visual map given as Supplementary Material.

(16% or $n = 67$), Region 4: Latin America and the Caribbean (3%, or $n = 11$), or Region 1: Africa & the Middle East (2%, or $n = 7$). No studies at all have been found for the subregions of Greenland, Bermuda and others; Caribbean; and Developing Pacific.

4.2. Narrative review: existing roadmaps

The list of 117 roadmaps, including their complete citations, is provided as Supplementary Material. It is by no means exhaustive, only an exemplary result of our search method, that we below analyze narratively, and serves to illustrate a series of key issues in the implementation of ZLECB worldwide.

The geographical inequalities found in the focus of the scientific literature are even more extreme in the focus of the roadmaps. Whereas most of the documents focus on developed countries (*i.e.* North America, Europe, Asia-Pacific developed), only a few documents are found for Asia and developing Pacific. Other regions such as Africa and Middle East, Latin America and the Caribbean are very little discussed.

Here, we touch on the research questions presented in section 2, and present a summary for each in corresponding columns of table 3. In the subsections below, the analysis for each of these developed world regions is presented, followed by the analysis of the remaining few documents found for other world regions.

4.2.1. European Union.

The EU and its Member States (MS) have provided the largest pool of relevant data for this study. The European Commission (EC) drafted a roadmap to climate neutrality by 2050 [Long Term Strategy (LTS) 2050 (EC 2018a) and the EU Green Deal (EC 2019a)] where the role of buildings is highlighted. The LTS states that from 2021 onwards and relying on ready-to-use technological solutions, all new buildings in the EU will have to be nZEB. To do so, buildings must incorporate energy-efficient envelope components, high performance technical building systems, and smart technologies and Information and Communications Technologies (ICT). Not only that, but the EC has set policy targets and regulations to ensure the energy efficiency improvement of the European building stock in the short term—including nZEBs. The Energy Performance of Buildings Directive (EPBD) (EC 2018b) is the main legislative and policy tool. It focuses on both new and existing buildings (EC 2012). At the same time, the building sector plays a prominent role in the Energy Efficiency Directive (EED) (EC 2012) that identifies the existing building stock as the single biggest potential sector for energy savings and, as a result, crucial to achieving the EU objective of reducing GHG emissions (EC 2016). What is more, the Renewable Energy Directive (EC 2019b) states that measures and policies on the minimum levels of RES in new and existing buildings should be present in national regulations and codes.

Most EU MS have roadmaps and policy frameworks being implemented at a national level by government agencies or at the national government level, following the guidelines by the EC and the directives in place. There is a great variability among MS when it comes to the implementation of regulations and

Table 3. Summarized assessment of the roadmaps, per world region, touching upon the research questions 1–4 presented in section 2. (1) Following the target assessment classification of section 3.4.2: (2) Following the four (i–iv) key components of the ZLECB of section 1.

	Number of roadmaps and organizational level	Target assessment and metrics (1)	Subsectors and building typologies	Components of ZLECB (2)	Evidence gaps
EU	Many: at EU level, requiring national transpositions	All 1–5 Varying metrics per MS	Existing and new buildings, additional focus on exemplary role of public buildings	All, using a flexible nZEB definition that allows each MS to optimize the weight of the components for each national context	-Progress monitoring, - Differences across countries in terms of goals and implementation strategies - Lack of a comprehensive retrofit implementation towards NZEB
North America	Many: at National, State/Provincial, and City scales with varying and uneven coverage, mostly lacking central coordination	All 1–5; varying metrics by location and scale (e.g. Objective 3 appliance efficiency specified at both the national (US) and state (CA) scale, but Objective 1, building codes, differs by state/-province and city)	Varies widely with some national goals targeting federally owned buildings, and more localized goals targeting a wider range of subsectors (residential/commercial, new/existing)	All to some extent, with lots of variation. Broadly, a larger emphasis on components i, ii, and iii (design, equipment, and renewable energy) and less focus on iv (sustainable materials), with some exceptions.	- Lack of identified central strategy between different levels of governance - Inconsistent or missing implementation, tracking, and enforcement strategies - Lack of coverage and calculation methods for embodied emissions - Weaker targets for building renovations
China	Many: at National level Five-Year-Plan and Provincial level (each province has its own Five-Year-Plan).	The main target is for the increase of energy efficiency. The target for ZLECB is on demonstration stage.	New buildings and existing buildings, Focus on public buildings and apartment blocks	Mostly i–iii: building envelope, windows, solar PV, geothermal, air source Heat pump	- Lack of coverage on evaluation and certification on goals for NZEB.
Other regions	A few in Asia and developing Pacific, almost none in the rest of the world regions	Insufficient data	Focus on new buildings in the few existing building codes	Insufficient data	- Lack of national roadmaps in most of the regions

the quantitative targets set. The priority for the nZEB implementation is that all new public buildings are constructed as nZEBs after 2018 and all new buildings are nZEB by the end of 2020 (EC 2018b).

Our compilation does not include all national transpositions, but rather illustrative examples. A summary of national regulation is found in the website of the EC.[6] For instance, Germany has in-depth strategies to achieve a carbon-neutral building stock by the year 2050 with several co-existing measures to achieve the targets (Schimschar 2013, Braune 2019). In contrast, Denmark has sufficiently low energy use intensity values allowed for buildings. Estonia has separate metrics for energy use for different types of buildings (D'Agostino 2015). These metrics correspond accordingly to detached residential buildings, apartments and commercial use buildings with further splits on the type (e.g. office buildings, hotels, public, etc.). Belgium has different energy use metrics for different regions, built into legislation (D'Agostino 2015). France applies central policies and metrics on the primary energy use for residential and commercial buildings. Cyprus has a split of the levels of primary energy use between residential and commercial buildings, as well. On the other hand, Ireland has a quantitative limit on the primary energy use of residential buildings, and Latvia the same value for all buildings. Spain applies different regional and national policies—with a specific quantitative target for hotels. The updated Spanish national building code provides maximum values in terms of primary energy consumption per use (residential/non-residential) and per climatic area for new buildings (RD 2019). Slovakia applies different limits on the primary energy use for residential (family houses and apartments) and commercial (office buildings and schools) buildings.

One example of flexibility can be found in the Swedish interpretation, where nZEB may be economically unviable if regulations were followed. The Nordic countries have a very low carbon energy system, low energy and carbon requirements also have to meet cost-efficiency levels and allow for local or regional boundaries, and the cost-optimal generation mix for heat from a societal (e.g. energy system) perspective. Relevant issues are how renewables on site are defined, in market competition with the grid, how the primary energy factors are defined, and how, if, exchanged energy can be accounted for, e.g. in clusters of buildings; all these issues require increased digitalization or smartness of demand-supply interactions.

4.2.2. North America.

In contrast to Europe, North American roadmaps identified tend to have clearly defined targets, but varying ranges of enforcement mechanisms on achieving those targets. North American roadmaps also typically set targets as a percentage reduction relative to baseline values instead of absolute metrics.

At the national scale, both the U.S. and Canada have roadmaps with whole-country targets. The U.S. Department of Energy sets energy efficiency goals including both the increasing the energy efficiency of new building technologies as well as targeting the energy intensity of buildings (U.S. Department of Energy 2016). Other relevant roadmaps at the U.S. federal scale include a presidential executive order for achieving zero energy status for all new government buildings by 2030 (US Executive Office of the President 2015), the National Aeronautics and Space Administration has compiled a roadmap for meeting that federal requirement (Pless *et al* 2014), (and the U.S. Department of Energy has also compiled goals for NZEB for the commercial sector (U.S. Department of Energy 2010). The Energy Information and Security Act also targets NZEB for all new commercial building construction by 2030, and for all buildings by 2050 (US 110th Congress, 2007). The Canadian national government has created a roadmap for reducing greenhouse gas emissions which includes goals such as a zero-energy ready building code by 2030 as well as increased existing building retrofits and efficient appliances (Canada 2016). In the U.S. and Canada, these national-level goals can be difficult to meet, as some of the mechanisms for implementation, such as building codes, are controlled at the state/-provincial or local level. As such, many regional and local governments have developed sub-national roadmaps.

At the state and province level, our search has identified roadmaps for California (CPUC 2015), British Columbia (BC 2017), and New York State (NYS 2014). Among these, California provides perhaps the most comprehensive plan of any state-level roadmap, outlining both short-term and long-term goals with milestones (Feng *et al* 2019). California is in a unique position compared to most American states in that they have their own building code developed and implemented for their entire state, allowing for new construction NZEB goals to be in lockstep with the building code being deployed. Similarly, provinces in Canada control building codes for the entire province, allowing for NZEB goals to be included in the code, as is the case for the British Columbian code requiring zero-energy ready buildings by 2032.

Roadmaps in North America are most prolific at the city-level, particularly in the U.S. Building codes are often specified and enforced at the city-scale, and cities often have the political nimbleness to enact more aggressive building roadmaps. For example, the City of Los Angeles released a comprehensive Green New Deal plan which addresses multiple facets of

[6] https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en

sustainability, including requiring all buildings, new and existing, to be net carbon neutral by 2050.

4.2.3. China.

In order to make more efforts to promote ZLECB and to be comparable to other countries, Chinese authorities issued their first National Standard for Nearly Zero Energy Building in 2019 (GB/T51350-2019 Technology Standard for Nearly Zero Energy Building). Under this standard, buildings need to be certified by government-appointed professional third parties to be regarded as NZEB. Every fifth year, the Chinese government issues five-year plans for important areas of social development including aspects of ZLECB. For instance, the latest five-year plans (2016–2020) issued by Ministry of Housing and Urban-Rural Development (MHURDC 2017a, 2017b, 2017c) and Ministry of Science and Technology (MOST 2016) separately emphasizes the promotion of NZEB.

For Chinese roadmaps, the targets are given in absolute metrics, *i.e.* in terms of net or gross built area. According to the plans, by year 2020 the energy efficiency of new buildings by floor area will be 20% better than the level in 2015, more than 500 million m^2 existing residential buildings and 100 million m^2 public buildings will be rebuilt to improve the energy efficiency, and the newly built area of NZEB demo projects will be more than 10 million m^2. Renewable energy, including solar, shallow geothermal, and air source heat pumps, are encouraged for new buildings.[7]

At the local government level, many provinces/-cities have issued local plans and corresponding financial subsidies to build more NZEB in recent years (DHURDSP 2020, DIITHP 2020). Different local subsidies include direct funds to the real estate developers (BMCHURD 2016) or government permits to sell at higher housing prices (SMPG 2018). According to some Chinese experts, 30% of new and 30% of existing buildings will be run on 30% renewable energy by 2030 (Liu *et al* 2019b).

4.2.4. Other world regions.

In the more developed world regions, other than for Europe and North America, we have found a few examples of roadmaps for Australia and other parts of Asia. Australia has plans at both national and local levels to reduce emissions through energy efficiency by the year 2030, with the City of Melbourne aiming for Zero Net Emissions by the year 2020 (Feng *et al* 2019; Tozer and Klenk 2018).

In the region of Asia and developing Pacific, other than for China, we have found examples for South Korea, Singapore, Malaysia and India. Singapore's Building and Construction Authority in 2014 introduced the Building Energy Efficiency roadmap to achieve improvements in the Energy Efficiency Index (EEI) by 40%–60% over 2013 best-in-class buildings by year 2030, along with the Super LEB Technology Roadmap to achieve improvements in the EEI by 60% over 2005 industry levels by 2018 and 80% by 2030 (Feng *et al* 2019). Malaysia's target is to reduce GHG emissions intensity of GDP by 45% by the year 2030 relative to 2005 levels (Feng *et al* 2019). For India, a recommendation has been provided to all relevant agencies since 2011 (Kapoor *et al* 2011), but no formal roadmap has been implemented so far. Although regulations like the Energy Conservation Building Code (ECBC Beeindia.gov.in. 2017) have come into effect for new buildings, there is still no formalized strategy roadmap for a country that is important for global climate change outcomes for India's size and scale, its rate of growth and its stage of development (Khosla and Janda 2019).

For Latin America and the Caribbean (subregion South America), Chile has a goal for ZLECB is included in the national energy strategy (Besser, and Vogdt 2017).

In the region of Africa and Middle East, we have only identified that South Africa (subregion Sub-Saharian Africa), through the C40 South Africa Buildings Program, seeks to implement net zero carbon performance for new buildings by 2020 (Feng *et al* 2019).

5. Discussion

We have tried to map and classify the worldwide evidence on roadmaps and target for zero energy buildings. We have retrieved 1219 scientific documents from the Scopus database, extracted metadata from 274 documents at title and abstract level, including type of study and geographical scope, and tagged them in a geographic map. By analyzing at the full text level 34 key documents, including scientific articles, grey literature, reference lists and tips from a reference group, we have identified 117 roadmaps, policies or plans from 37 countries worldwide. We have listed these documents and provided a narrative synthesis. While the compilation of roadmaps and policies (of Supplementary Material 2) is not exhaustive but exemplary, it has made clear that there is no compilation of relevant references worldwide and that there is an attention bias towards more developed regions.

As the intention of this paper is to map the extent and distribution of existing evidence on this topic, we do not go into detail about all the research articles found because we have not performed a critical appraisal of the included papers. This means that any type of review on effectiveness would be premature and unreliable. On top of that, recent reviews of the

[7]We have not been able to monitor the accomplishment of these targets for year 2020.

knowledge gluts, e.g. on case studies (Ürge-Vorsatz *et al* 2020) or technologies (Cabeza and Chàfer 2020), already exist. Nevertheless, we make below a narrative assessment of the validity of our findings by comparing to, and discussing, related literature.

5.1. Reaching decarbonization targets

We find that current efforts to implement ZLECB taken by different countries are not enough to achieve the global climate targets.[8] First, the lack of scientific literature and roadmaps in many world regions, and notably in Latin America and Caribbean as well as in Africa and Middle East, suggests that little focused progress is being made in the implementation of ZLECB in these regions. These world regions represent an area for further investigation and increased research/policy attention. Second, the more substantial amount of literature and roadmaps from more developed regions indicates where there has been significant research/policy attention given the volume of information that has been produced. Our rapid assessment of the literature and roadmaps, with respect to their amount, dates of approval and timelines, consistency and apparent limitations, suggest that efforts in these regions are not at the level described earlier in section 1. Our conclusion seems in agreement with the literature. For instance, Langevin *et al* (2019) ran various simulations of CO_2 emissions reductions from buildings in the US through 2050, and concluded none of them reached 80%, although the scenarios that came closest involved national-scale fuel switching, carbon pricing, and massive decarbonization of the electric grid; the regional patchwork nature of US roadmaps is unlikely to create these sufficient supporting conditions. Studies for the EU have found that energy savings for year 2020 projected in the National Energy Efficiency Action Plans appear to be overly optimistic when one considers the efficiency trends, current regulatory framework, and techno-economical potential detailed in this study (Mata *et al* 2018). The European policy scenario EUCO3232.5[9] foresees an annual CO_2 emission reduction for the period 2020–2023 in the residential and tertiary sector of 5.7% moving from more than 600 $MtCO_2$ eq. in 2020 to 336 $MtCO_2$ eq. in 2030. Still, the historical energy consumption trend between 2013 and 2018 shows that MSs have to enhance their commitments to ensure energy targets toward 2030 and 2050 (Zangheri *et al*2019). On top of that, the building characteristics, building ownership, and the construction sector are naturally fragmented in the EU, so that no single solution for the EU building stock is identified, which hinders the transformation of the building stock (Meijer *et al* 2009, Sandberg *et al* 2016, Filippidou and Jiménez Navarro 2019).

Modelling studies for China show that total CO_2 emission will not peak before 2030–45, depending of the scenarios and show that although various technological solutions, systems and practices can be very effective in minimizing building energy use, rigorous policies—beyond the existing—are needed to overcome multiple implementation barriers (Eom *et al* 2012; Zhou *et al* 2018, Tan *et al* 2018). A modeling study for India shows that as a result of population and economic growth, total Indian residential energy use is expected to increase by around 65%–75% in 2050 compared to 2005, but residential carbon emissions may increase by up to 9–10 times the 2005 level (van Ruijven, *et al* 2011).

Nevertheless, the identified documents for more developed regions represent areas where it would be particularly useful to conduct more in-depth syntheses such as a systematic review that could look closely at direction and magnitude of impacts and the influence of contextual factors.

5.2. Design of roadmaps

The roadmaps we examined often suffered from 3 deficiencies: (1) lack of specific, quantitative metrics on ZLECB goals, (2) lack of enforcement mechanisms for ensuring goals are met, (3) lack of technical analysis for identifying pathways to meet the goals, and (4) weaker goals for building renovations. At EU level, the targets set to achieve the global climate goals are ambitious. In addition to this and despite the fact that mandatory energy performance standards are progressively converging towards NZEB in the EU, the implementation of those standards remains at the discretion of MS, leading to large discrepancies (Economidou *et al* 2020). McLaren & Markusson (2020) look at the co-evolution of climate policies and technological modeling/advancement in a way that allowed for climate action to be pushed into the future, while prevented mitigation from occurring. The interdisciplinary nature of the NZEB concept needs further cooperation among all the actors involved in the area (D'Agostino and Mazzarella 2018). Previous literature shows that in many instances ZEB can be capital cost neutral, but that barriers exist in fully integrating these ideas into building design (Torcellini *et al* 2015). These relevant actors will only ensure an effective transformation of the building sector if they design strategies that combine building standards, the decarbonization of the energy supply sector (Pitts 2017; Belussi 2019, Filippidou and Jiménez Navarro 2019) and the integration of decentralized RES sources (Belussi 2019, Magrini 2020).

Furthermore, developing strategies will require an understanding of how the large-scale drivers of

[8] With the exception of India, for which Dubash *et al*, (2018) conclude that the likely development of India's CO_2 energy-related emissions is consistent with meeting India's Paris emissions intensity pledge. This trajectory, based on current policies, points at a doubling of India's CO_2 energy-related emissions from 2012 levels is a likely upper bound for its 2030 emissions. The specific role of the buildings sector therein is however unclear.

[9] https://ec.europa.eu/energy/data-analysis/energy-modelling/euco-scenarios_en

building energy demand might unfold. For example, the US Energy Information Administration periodically does a survey of commercial building energy use in the county, and finds that energy use is driven by a combination of changes in (1) mix of economic activities (e.g. health care, retail, food service etc.); (2) regional distribution of buildings; and (3) average sizes of buildings (Hojjati and Wade 2012). Similarly, Ma *et al* (2019) find that three housing economic indicators (housing purchasing power, housing price-to-income ratio, and population size per household) have contributed significantly to decrease CO_2 intensity in China. However, under major systematic changes, the fundamental relationships underlying the correlation between commercial buildings and energy use might change. This has become strikingly apparent under COVID-19 restrictions in many countries, as commercial buildings are occupied less frequently in aggregate, but when they are occupied, they use an increased amount of ventilation to reduce potential disease transmission. Although not all of the changes in energy use behavior from COVID-19 will persist in the long-term (although some might), this type of radical behavior change is an important point to consider when testing the sensitivity of different models underlying technology mitigation models.

Hong *et al* (2016) suggest for China that first, policies are oriented to curb the fast growth of building floor space, second, current building energy retrofit targets and initiatives are reinforced as well as more stringent energy performance standards for new constructions promoted, and last, the average building lifetime has to be prolonged in order to conserve energy and re-sources. Indeed, retrofitting is to play a crucial role in the transformation of the building sector. In old building stock, such as the European, renovation is deemed the only way to achieve the decarbonization goals. However, NZEB renovation poses several challenges including the need of a holistic approach (traditionally renovation has focused on the reduction of energy consumption) (D'agostino *et al* 2017), the importance of exemplary cases and well informed users and practitioners (Pitts 2017) or the need of more robust concepts and definitions that can be largely applied and not only to specific cases as literature review shows (Attia *et al* 2017) and ultimately adequate supporting mechanisms (Patiño-Cambeiro *et al* 2016). Similar conclusions are reached by others, as it is agreed that to reach ZLECB performance, requires passive strategies, energy efficient technologies, and then RES generation systems (Harkouss *et al* 2018). These key components, which interplay results in a large variety of pathways for each specific case, are discussed below.

5.3. Technologies

There is a lack of specific technical building system solutions in most of the roadmaps examined, probably because there is also an understanding that to achieve ZLECB a combination of solutions is required (Blonsky *et al* 2019; Reda and Fatima 2019). In Europe, the energy efficiency-principle-first applies, and demand for energy is to be reduced, e.g. greater thermal insulation of building envelopes, even more for renovations of existing buildings. Then, the deployment of mature and more efficient technologies, such as heat pumps or cogeneration, can also increase the rates of implementation of the roadmaps in place (Filippidou and Jiménez Navarro 2019). Reda and Fatima (2019) in a study of nZEB concepts for Northern European countries, identifies that many nZEB concepts can be achieved by adopting more energy performant building design principles and/or installing onsite solar technologies. Similarly, in China, certain major technologies are identified, such as insulation of the building envelope (including windows), heat recovery systems in combinations with RES technologies such as solar PV, solar thermal system, geothermal and air source heat pump, wind power system (Liu *et al* 2019a).

Technology mitigation strategies are potentially even more complicated in regions that might have both significant increases in cooling loads and decreases in heating loads under future climate scenarios. Zhou *et al* (2013) do a comparative study of future climate changes on energy demand in the US and China and find modest decreases overall with heating demand decreases offsetting cooling demand increases. In a study of southern California in the US, Reyna and Chester (2017) find that new adoption of air conditioners in previously uncooled homes combined with increased cooling needs under future climate scenarios leads to a slight increase in overall energy demands. Both of these studies exemplify the need to consider future climate and how it might influence technology adoption and use in developing technology solutions for roadmaps.

Finally, technological changes in material manufacturing are also relevant, as exemplified in an analysis that finds that the Swedish construction sector can only reach maximum climate change mitigation scenarios if the low-impact building typologies are implemented together and rapidly (Peñaloza *et al* 2018).

5.4. Demand-supply interactions

The building sector is intertwined with other sectors such as the power sector. While our review focuses on the building sector, deep carbon reductions from buildings will only be possible together with decarbonization strategies beyond the built environment and additional supporting mechanisms, such as carbon pricing.

The future heating and cooling and electricity supply fuel mixes play a vital role in the decarbonization of the EU building sector (Filippidou and Jiménez Navarro 2019). As an example, Reda and

Fatima (2019) conclude that the selection of the right building design principles, typology and size of solar technologies depends on the main building heating source; typically, district heating and ground source heat pumps in Nordic countries. For Chinese buildings, Ma *et al* (2019) have identified that the 'coal to electricity' effect of the residential building sector is significantly reduced final emission factor on CO_2 intensity of Chinese buildings over the past decade; Eom *et al* (2012) have identified that, regardless of the scenarios, the growth will involve the continued, rapid electrification of the buildings sector throughout the century, and this transition will be accelerated by the implementation of carbon policy; Tan *et al* (2018) further identify that the most important reason why the carbon emissions of some scenarios peak before 2030 is the decrease of the power and heat emission factors. Studies for India show while a more equal income distribution and rural electrification enhance the transition to commercial fuels and reduce poverty, there is a trade-off in terms of higher CO_2 emissions via increased electricity use (van Ruijven *et al* 2011), at the same time, recent policy trends suggest a lower than expected electricity demand and a faster than expected transition from coal to renewable electricity (Dubash *et al* 2018).

Even more, a deep demand reduction based on a large ZLECB deployment may stress the power system requiring more flexible supply options (Seljom *et al* 2017, Mata *et al* 2020b). Reda and Fatima (2019) conclude that at northern latitudes the energy generated onsite with conventional solar technologies is not enough to reach the net zero energy target, and that seasonal storage and advanced 'building to urban energy networks' solutions could go beyond, and even achieve PEBs.

5.5. Life-cycle perspectives and embodied emissions

Embodied emissions from buildings are present in all building life cycle steps: construction, maintenance, and demolition. Rarely are they included in roadmaps because of the complexity of calculation and the occurance of these emissions outside national boundaries, but it is an important point as some ZLECB technologies might have substantial embodied GHG (Dissanayake *et al* 2017). The improvement of resource flows through a circular and sharing economy principles by reducing, reusing, recycling, and recovering (Eberhardt *et al* 2019, Mata *et al* 2020), allows to decouple growth from resource consumption and has environmental advantages, contributing to climate change mitigation (ECOFYS 2016, Nasir *et al* 2017). Although the literature recognizes urgent needs to reduce embodied impacts and for strategies to convince all stakeholders, the there are few explicit links to climate mitigation (Górecki *et al* 2019, Röck *et al* 2020). Transition to the era of circular and shared economy aligned with climate goals requires changes in household behavior, design practices, construction and de-construction methods, and business models as well as organizational and legal frameworks (Górecki *et al* 2019, Badi and Murtagh 2019, Jayasinghe *et al* 2019).

5.6. The role of regions and cities

It has become clear that an important pathway to success will be through the engagement of subnational entities, generally, and cities, specifically (Solecki *et al* 2018). Limiting warming to 1.5 °C requires cities to mitigate, while also preparing for the impacts of a warmer world. We have identified many roadmaps at regional and urban levels in more developed regions. For instance, nearly all major U.S. cities have developed some level of climate change roadmap, many of which set building targets. Deetjen *et al* (2018) provide a comparative overview of climate action plans from 29 major U.S. cities. Many EU projects have demonstrated the feasibility of nearly-zero energy building renovation models in view of triggering large-scale, Europe-wide replication in smart cities and communities.[10] Beyond our compilation, a study of a representative sample of 885 European cities shows that about 80% of the cities with above 500 000 inhabitants have a comprehensive and standalone mitigation and/or an adaptation plan (Reckien *et al* 2018). Whereas this is a major increase compared to an earlier analysis,[11] still only a minority of urban areas consider both mitigation and adaptation in their climate action plans (Grafakos *et al* 2020).

At the same time, the lack of roadmaps in many world regions is most concerning, as building infrastructure for fast-growing cities in developing countries could release 226 Gt CO_2 by 2050, more than four times the amount used to build existing developed-world infrastructure (Müller *et al* 2013, Bai *et al* 2018). Along these lines, Solecki *et al* (2018) identifies that efforts in urban planning and capacity-building strategies to tackle increasing vulnerability to extreme events and growing demands for a transition to a low carbon economy must now shift to hyper-speed, especially in the Global South where rapid urbanization, climate change vulnerability, and environmental justice collide.

The role of cities in the context on climate change, including research priorities and locking of positive climate response, is discussed by (Bai *et al* 2018, Ürge-Vorsatz *et al* 2018).

[10]For instance: EU-GUGLE (http://eu-gugle.eu/project/); AZEB | Affordable Zero Energy Buildings (https://azeb.eu/); ZEBRA2020 | Nearly Zero-Energy Building Strategy 2020(https://zebra2020.eu/); RenoZEB (https://renozeb.eu/).

[11]An analysis of 200 large and medium-sized cities across 11 European countries showed that 35% of European cities had no dedicated mitigation plan and 72% had no adaptation plan (Reckien *et al* 2014).

6. Conclusions

We find that there is an attention bias towards more developed regions. Most of the documents focus on Europe, some on North America, and significantly less on Asia and Australia. These studies are mostly recommendations to policy makers, and different types of case studies and demonstration projects. A wide range of energy efficiency measures and renewable energy technologies, prefabricated buildings and passive house technologies are addressed.

The geographical inequalities found in the focus of the scientific literature are even more extreme in the focus of the roadmaps. Whereas most of the documents focus on developed countries (*i.e.* North America, Europe, Asia-Pacific developed), only a few documents are found for Asia and developing Pacific. Other regions such as Africa and Middle East, Latin America and the Caribbean are not frequently discussed. This suggests that little progress is being made in the implementation of ZLECB. These world regions represent an area for further investigation and increased research/policy attention.

Our rapid assessment of the more substantial amount of literature and roadmaps for more developed regions, with respect to the amount, dates of approval and timelines, consistency and apparent limitations, suggest that efforts in these regions are not enough to achieve the global climate targets. Concrete roadmaps, in the form of action plans with well-defined goals and targets, exist in these regions. They all show a variety of efforts being applied at different levels—from national to local. Still, the strategies observed are different in metrics for the targets and in mechanisms to enforce them. New and public buildings are generally more the focus than existing buildings, whereas the latter are naturally larger in number and total floor area, and tend to be less energy efficient. A combination of envelope and technical systems upgrades together with the promotion of renewables is generally put forward, with behavioral measures only implicit in the use of ICT. Less focus is found in lifecycle perspectives and embodied energy and carbon.

More work is needed to couple the existing ambitious climate goals, with realistic, enforceable policies to make the savings a reality for different contexts and stakeholders worldwide.

Acknowledgments

Lin Liljefors (Boverket, Sweden), Rajan Rawal (CEPT, India), and Åsa Wahlström (CIT Energy Management, Sweden), as well as two others who prefer to remain anonymous, are gratefully acknowledged for the contributions as members of the reference group. A part of this work has been conducted by A.K. Korpal as a MSc Thesis (Korpal 2020). This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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